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Electron Cooling in a Normal-Metal Hot-Electron Bolometer

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Normal-metal hot-electron bolometers, each of which contains two superconductor–insulator–normal metal (SIN) junctions for electron cooling and two SIN junctions for temperature measurements, were fabricated and experimentally studied. The electron cooling by SIN junctions is an analog of the Peltier effect and allows one to reduce the effective electron temperature of a bolometer. The electron temperature was determined from the ratio of the differential resistance to normal one for several values of a constant bias. At a phonon temperature of 250 mK, the resistance ratio at zero bias reached 1000, which was close to the theoretical value for an ideal SIN junction. A decrease in the electron temperature from 250 to 90 mK was obtained. © *2003 MAIK "Nauka/Interperiodica".*

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Normal-metal hot-electron bolometers with capacitive coupling were proposed in [1] and experimentally studied in [2]. The main characteristics of a bolometer, namely, the response and the noise-equivalent power (NEP), are determined by its electron temperature. A way of improving these characteristics by using an electron cooling with the help of superconductor–insulator–normal metal (SIN) junctions was proposed in [3]. A direct electron cooling was demonstrated in [4] and further developed in [5]. Two SIN tunnel junctions can be used for both electron cooling in the normal metal and measuring the response of the bolometer to an external signal. The electron cooling is an analog of the Peltier effect known since 1834 for a pair of junctions formed by different metals: when current flows through the junctions, one of them is heated and the other is cooled. The principle of cooling by SIN junctions is similar to blowing hot vapor away from the surface of hot tea in a cup. Hot electrons with energies above the Fermi level are removed from the normal metal via one junction and cold electrons with energies below the Fermi level are supplied to the normal metal via the other junction. This is the main qualitative distinction from the Peltier effect, because both SIN junctions participate in cooling of the normal metal lying between them. Cold electrons with energies below the Fermi level can also be considered as hot holes removed via the second SIN junction. A simple estimate of the power eliminated in this way can be made by assuming that, at a bias near the energy gap, each electron participating in the current removes the energy smaller than or about k_bT. Then, the power eliminated by a current I is about Ik_bT/e. For an efficient cooling, it is necessary to have a channel for heat removal by the current of hot quasiparticles with energies above the superconducting energy gap. This is achieved with the help of the normal-metal traps. Evidently, a decrease in the electron temperature leads to an increase in the temperature response, which makes it possible to reduce the contribution of noise of the subsequent amplifier and the NEP.

Principles of temperature measurement by superconducting tunnel junctions. To estimate the electron temperature, we can use the approximation of the current–voltage (I–V) characteristic of a real junction by the I–V characteristic of an ideal SIN junction. For the latter, the following simple expression is valid:

$$I(V, T) = \frac{1}{eR_N}\sqrt{2\pi k_b T\Delta}\exp\left(-\frac{\Delta}{k_bT}\right)\sinh\left(\frac{eV}{k_bT}\right), \quad (1)$$

where R_N is the normal resistance of the junction, T is the temperature, Δ is the energy gap of the superconductor, e is the electron charge, k_b is the Boltzmann constant, and V is the voltage. The subgap leakage current due to the nonideal structure of the SIN junction can modify the I–V characteristic and considerably affect the response of the bolometer. In addition to the defects of the tunnel junction, the I–V characteristic of a highly transparent junction can also be affected by the two-electron tunneling current, when two electrons form a Cooper pair [6]. As was noted in [7], a decrease in the barrier thickness leads to an increase in the contribution of Andreev reflection. At temperatures below 200 mK, an inverse tunneling of quasiparticles from the superconductor to the normal metal is possible [8] and an inverse absorption of phonons may also occur after the recombination of quasiparticles. Without special traps for hot quasiparticles, the effect of electron cooling may be considerably suppressed. In the experiments [9], a temperature saturation was observed below 300 mK, when hot quasiparticles are in the normal-metal trap.

For real junctions, it is important to estimate the effect of point defects of the tunnel barrier. The defects determine the residual resistance at zero bias. For a typical junction with a normal resistance of 1 kΩ at 300 mK, the differential resistance in the absence of bias should be greater than 1 MΩ. If we take the leakage resistance equal to this value, i.e., 1 MΩ, the electron temperature due to the Joule heating will be expressed as

$$T_e = \left(T_{ph}^5 + \frac{P}{\Sigma v}\right)^{1/5}, \quad (2)$$

where P is the power scattered by the leakage resistance, $\Sigma = 3 \times 10^9$ W m^{-3} K^{-5} is the characteristic constant of the normal metal, and $v = 0.18$ μm^3 is the volume of the normal metal. For zero phonon temperature at a standard bias of 400 μV, we obtain a temperature increase of 200 mK. For a smaller bias of 100 μV, we still obtain an overheating of 115 mK. An increase in the leakage resistance to 10 MΩ reduces the overheating to 127 mK at a bias of 400 μV. This means that even a very small measuring current of the thermometer may cause a considerable increase in the electron temperature above the phonon temperature and introduce an error in the temperature measurement. Let us estimate the possibility of applying the resistance ratio criterion to temperature measurements by a real junction. For this purpose, we introduce a shunting resistance R_s of the leakage current into Eq. (1) and obtain the relative differential resistance in the form

$$r = \left[\left(\sqrt{\frac{k_bT}{2\pi\Delta}}\frac{\exp(\Delta/k_bT)}{\cosh(eV/k_bT)}\right)^{-1} + \frac{R_n}{R_s}\right]^{-1}. \quad (3)$$

This kind of temperature dependence calculated for the standard parameters of one of our samples is shown in Fig. 1. One can see that, at zero bias, a saturation of the thermometer is observed as early as at 200 mK, while at relatively high biases, the thermometer retains a high sensitivity. To measure lower temperatures, it is necessary to use greater bias voltages at which the differential resistance is smaller than the leakage resistance. For choosing the bias voltage, the following simple criterion can be used: at temperatures below 200 mK, the resistance ratio should be measured at a bias voltage of 250 μV at the thermometer, and below 100 mK, at a bias of 300 μV.

Electron cooling by SIN junctions. For the cooling power, we write a simple analytical expression:

$$P_{\text{cool}}(T_e, V) = \frac{\sqrt{2\pi\Delta k_bT_e}}{2eR_N}\left(\frac{\Delta}{e} - V\right)\exp\left(-\frac{\Delta - eV}{k_bT_e}\right). \quad (4)$$

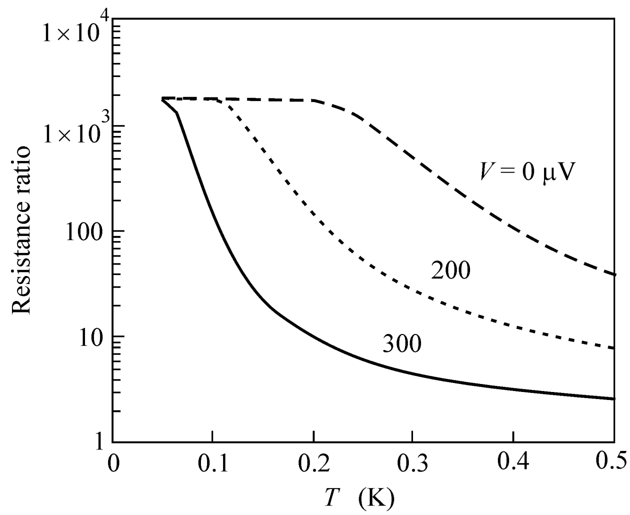

Fig. 1. Temperature dependences of the resistance ratio at zero bias and at biases of 200 and 300 μV. The dependences were calculated for a thermometer with a normal resistance of 10 kΩ and a leakage resistance of 35 MΩ.

The effective electron temperature T_e is determined from the heat balance equation

$$(T_{ph}^5 - T_e^5)\Sigma v = P_{\text{cool}}(T_e) - P_{bg} - V^2/R_s, \quad (5)$$

where T_{ph} is the phonon temperature, V is the constant bias voltage, R_s is the shunting leakage resistance, $P_{bg} = 0.5hf\Delta f = 6 \times 10^{-14}$ W is the background radiation power, $\Sigma = 3 \times 10^9$ W m^{-3} K^{-5} is the parameter of the absorber material, and $v = 1.8 \times 10^{-19}$ m^3 is the volume of the absorber. A graphical solution of Eq. (5) is shown in Fig. 2, where curve P_{ep} corresponds to the electron–phonon energy transfer $P_{ep} = (T_{ph}^5 - T_e^5)\Sigma v$ at a phonon temperature of 250 mK and curves P_V correspond to the cooling or overheating powers $P_V = P_{\text{cool}} - V^2/R_s - P_{bg}$ in the bolometer. From these dependences it follows that, at a leakage resistance of 30 MΩ, one can obtain an electron cooling of $\Delta T = 160$ mK at a phonon temperature of 250 mK.

Such a noticeable decrease in the electron temperature should lead to a considerable improvement of the bolometer parameters and, in particular, to an increase in the temperature response dV/dT_e. If we approximate the I–V characteristic of the SIN junction by the expression [9]

$$I(V) = I_0 e^{(eV-\Delta)/k_bT_e}, \quad I_0 = \frac{\sqrt{2\pi\Delta k_bT_e}}{2eR_N},$$

the maximal temperature sensitivity should be observed at zero bias and be equal to

$$\frac{dV}{dT_e} \cong \frac{k_b}{e}\ln\frac{I}{I_0} = \frac{k_b}{e}\frac{eV - eV_\Delta}{k_bT_e} = -\frac{V_\Delta}{T_e}. \quad (6)$$

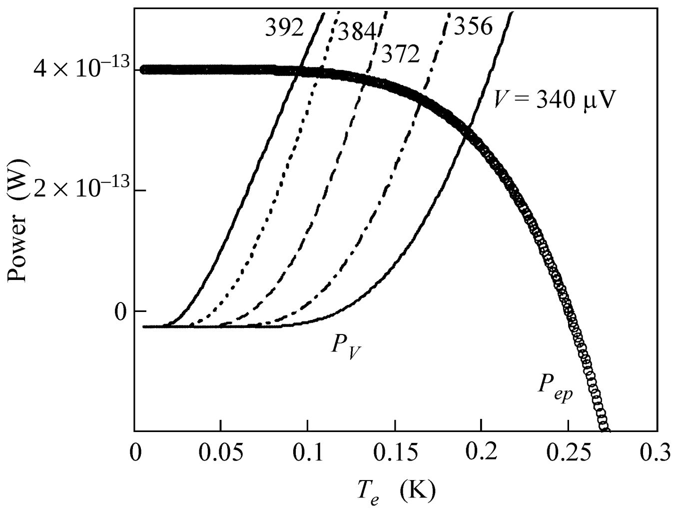

Fig. 2. Curve P_{ep} corresponds to the electron–phonon power transfer $P_{ep} = (T_{ph}^5 - T_e^5)\Sigma v$ at a phonon temperature of 250 mK; curves $P_V = P_{cool} - V^2/R_s - P_{bg}$ correspond to the cooling and heating power balance in a bolometer with the bias voltages at the cooling junctions within 392–340 μV. The intersection of curves P_{ep} and P_V yields the value of the stable electron temperature T_e in equilibrium.

Evidently, a twofold decrease in the electron temperature leads to a twofold increase in the temperature response. This allows one to reduce the contribution of noise from the subsequent amplifier and, hence, to reduce the NEP. However, in a real junction, such high response values cannot be obtained because of the parasitic leakage resistance. Now, if, for temperature measurements, one uses the same SIN junctions as those used for cooling with the bias chosen to satisfy the condition $eV - \Delta = k_bT$, the response becomes equal to

$$dV/dT_e = (T/T_e)k_b/e. \tag{7}$$

Then, the NEP proves to be considerably reduced in both cases:

$$NEP^2 = 4k_bT_e^2G. \tag{8}$$

As a result, in the example considered above, a temperature decrease from 250 mK to less than 100 mK corresponds to a decrease in the NEP by a factor of 2.5.

EXPERIMENT

For the sake of comparison with the theoretical estimates, in Fig. 3 we present the experimental dependences of the differential resistance of SIN thermometers on the bias voltage of the cooling junctions at a phonon temperature of 20 mK. One can see that the maximal resistance of 45 MΩ is observed at zero bias at the cooling junctions. Any finite bias voltage reduces the resistance below 37 MΩ, i.e., leads to an overheating above 20 mK instead of cooling. An increase in the resistance of the thermometer biased by 200–350 μV with a cooler biased by 400 μV corresponds to the expression for the resistance ratio at a finite bias, when the cooling from the bias-overheated thermometer (98 mK) to an electron temperature of 88 mK takes place. Similar dependences measured at a phonon temperature of 250 mK (Fig. 3) exhibit a growth of the resistance of the unbiased thermometer from 12 to 36 MΩ with increasing bias at the cooler. The resistance of the thermometer at this phonon temperature is not as strongly shunted by leakage, and the electron temperature can be estimated from the resistance ratio at zero bias according to Eq. (3). The resistance ratio at

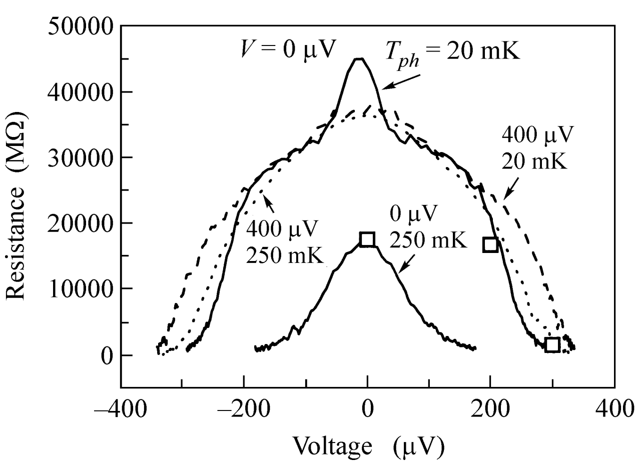

Fig. 3. Dependences of the differential resistance of an SIN thermometer on its bias voltage. The dependences were measured at phonon temperatures of 20 and 250 mK with two bias voltages at the cooler: 0 and 400 μV. Theoretical values from Fig. 1 are presented for three bias voltages at the thermometer: 0, 200, and 300 μV.

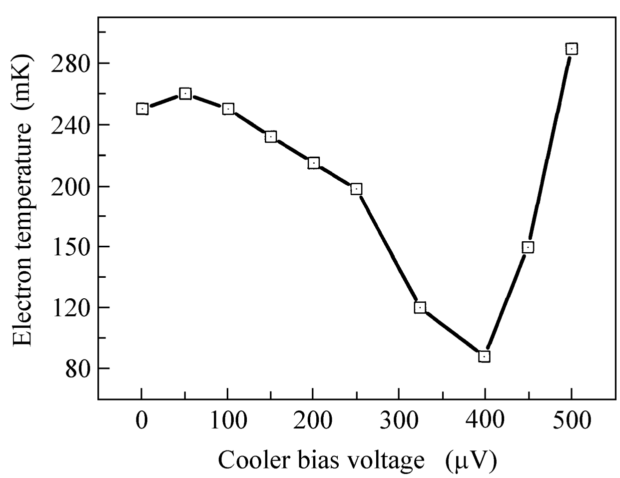

Fig. 4. Equivalent electron temperature obtained from the resistance ratio at a bias of 300 μV.

a thermometer bias of 300 μV (Fig. 4) yields a decrease in the electron temperature from the equilibrium phonon temperature of 250 down to 88 mK, i.e., by 162 mK. A noticeable difference between theory and experiment is observed for zero bias at both thermometer and cooler, when the resistance drastically increases above the expected leakage resistance. We assume that this effect is related to the Coulomb blockade in the small bridge separated from the electrodes by tunnel junctions. The slight deviation from the theory that was observed with a bias of 200 μV at the thermometer may be related to an additional cooling of the absorber phonon system due to the electron cooling.

The limiting parameters of a normal-metal hot-electron bolometer strongly depend on the overheating by the external background radiation and the overheating by the leakage current through the defects of the tunnel barriers in the tunnel junctions of both thermometer and cooler. The real electron temperature of the bolometer may exceed the phonon temperature by 100 mK or more. The use of electron cooling makes it possible to considerably reduce the effect of this parasitic overheating and to improve the bolometer characteristics. In our samples at a temperature of 250 mK, the use of electron cooling allowed us to increase the temperature response from 1.6 to 2.1 mV/K, which corresponds to Eq. (7) for not strongest possible cooling and not optimum bias. Theoretical estimates made for an ideal SIN junction yield greater values for electron cooling and greater improvement for the bolometer parameters. However, in real junctions, the presence of the shunting leakage resistance considerably affects the results.

CONCLUSIONS

Thus, we developed, fabricated, and studied normal-metal hot-electron bolometers with an electron cooler on the basis of a superconducting tunnel junction. The electron cooling makes it possible to increase the response of the bolometer and to reduce the NEP. To estimate the electron temperature, we suggested to use the criterion of the resistance ratio of the tunnel junction at finite bias voltages. We obtained a cooling of the electron subsystem from the equilibrium phonon temperature of 250 mK down to 90 mK.

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